An Observational and Modeling Study of Air-Sea Fluxes at Very High Wind Speeds

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Grant Number: N00014 01-1-0162
http://www.aoml.noaa.gov/hrd/cblast/

LONG-TERM GOALS

Our ultimate objective is to understand and be able to predict changes in the intensities of hurricanes. Over the last three decades, there has been considerable improvement in both our understanding and our ability to predict the tracks of hurricanes, but there is, by contrast, little skill in predicting hurricane intensity change.

OBJECTIVES

The objective of the work carried out under this grant is to understand and be able to model fluxes of enthalpy, moisture and momentum between the ocean and atmosphere in all ranges of wind speed, up to and including wind speeds encountered in severe hurricanes. Modeling such fluxes is critical to predicting hurricane intensity.

APPROACH

Our approach is to use atmospheric measurements collected in actual hurricanes to deduce surface fluxes of enthalpy and momentum. These measurements consist of wind, temperature and humidity measured directly from research reconnaissance aircraft and from GPS dropwindsondes deployed from those aircraft. Such measurements are first used to construct the azimuthally averaged radius-height distributions of angular momentum, moist static energy and radial velocity. Then, assuming that the storm is in an approximately steady state, the radial advections of moist static energy and angular momentum are calculated, and the surface fluxes of angular momentum and enthalpy are deduced as those needed to maintain a steady state. This approach has been taken (for angular momentum only) by (Hawkins and Rubsam, 1968), but they had to rely on measurements somewhat inferior to those available today. Our work is being carried out under the leadership of the principal investigators Kerry Emanuel of MIT, who is supervising the analysis of the aircraft and dropwindsonde data, and Peter Black of the NOAA/AOML Hurricane Research Division, who is providing the aircraft data and using

Report Documentation Page			*Form Approved OMB No. 0704-0188*
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1. REPORT DATE **30 SEP 2003**	2. REPORT TYPE		3. DATES COVERED **00-00-2003 to 00-00-2003**
4. TITLE AND SUBTITLE **An Observational and Modeling Study of Air-Sea Fluxes at Very High Wind Speeds**			5a. CONTRACT NUMBER
			5b. GRANT NUMBER
			5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)			5d. PROJECT NUMBER
			5e. TASK NUMBER
			5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Room 54-1620, MIT,,77 Massachusetts Avenue,,Cambridge,,MA,02139**			8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)			10. SPONSOR/MONITOR'S ACRONYM(S)
			11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**			
13. SUPPLEMENTARY NOTES			
14. ABSTRACT			
15. SUBJECT TERMS			

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**6**	

the early results of our research to plan field operations during the second and third years. Analysis of the existing aircraft data is being carried out by William Ramstrom, an advanced graduate student at MIT. The approach we are taking under this grant compliments a laboratory modeling approach we are using under separate funding.

WORK COMPLETED

As planned for the first year of our work, we completed an analysis of existing aircraft and GPS dropwindsonde data and published the results as a Master's Thesis (Ramstrom, 2001). During the second year, we conducted a preliminary field campaign in which we tested our strategy for deploying a dense line of GPS dropwindsondes across the eyewalls of Atlantic hurricanes, coupled with detailed aircraft measurements of turbulent fluxes across the top of the inflow layer. This was performed in Hurricane Isidore. During this third year, we were successful in deploying dense arrays of dropwindsondes in Atlantic Hurricanes Fabian and Isabel, supplemented in most cases by AXBT measurements of local sea surface and sub-surface temperature and by direct enthalpy and momentum flux measurements from two WP-3D aircraft. We believe that these measurements will allow us to make accurate estimates of surface enthalpy and momentum fluxes using the budget residual technique, as proposed.

RESULTS

Until CBLAST, field measurement programs were not developed with the kind of analysis we are now undertaking in mind, and consequently there are strong limitations to what can be done with them. Nevertheless, we were able to deduce surface drag coefficients in a number of hurricanes that show remarkable consistency with previous inferences and with very recent laboratory experiments. The 10 meter drag coefficients varied between 0.0027 and 0.0030 for wind speeds in the 40-60 m s^{-1} range, with some tendency to increase with wind speed, although the spatial density of measurements did not allow us to infer a meaningful relationship between the drag coefficient and wind speed. As expected, we did not see much evidence for strong vertical turbulent fluxes of angular momentum out of the top of the boundary layer.

Deduction of the surface enthalpy fluxes, here attempted for the first time, proved more problematic, as in most of the storms we surveyed, the turbulent entropy flux out of the top of the boundary layer was comparable in magnitude to the inferred surface fluxes. These turbulent fluxes had to be inferred from aircraft data, but the aircraft flight tracks were not ideally suited to the task. Our best estimates of the 10 meter exchange coefficient for enthalpy are very comparable to the drag coefficient values, indicating that the ratio of the exchange coefficients for enthalpy and momentum is nearly unity.

We also developed a technique for calculating the ratio of the exchange coefficients directly from the radial distributions of angular momentum and moist static energy, without having to use the radial velocity, which is very sensitive to errors in the location of the center of the storm. The ratio can be estimated directly from the gradient of moist static energy with respect to potential radius, which is a measure of the angular momentum per unit mass. An example of such a calculation is shown below.

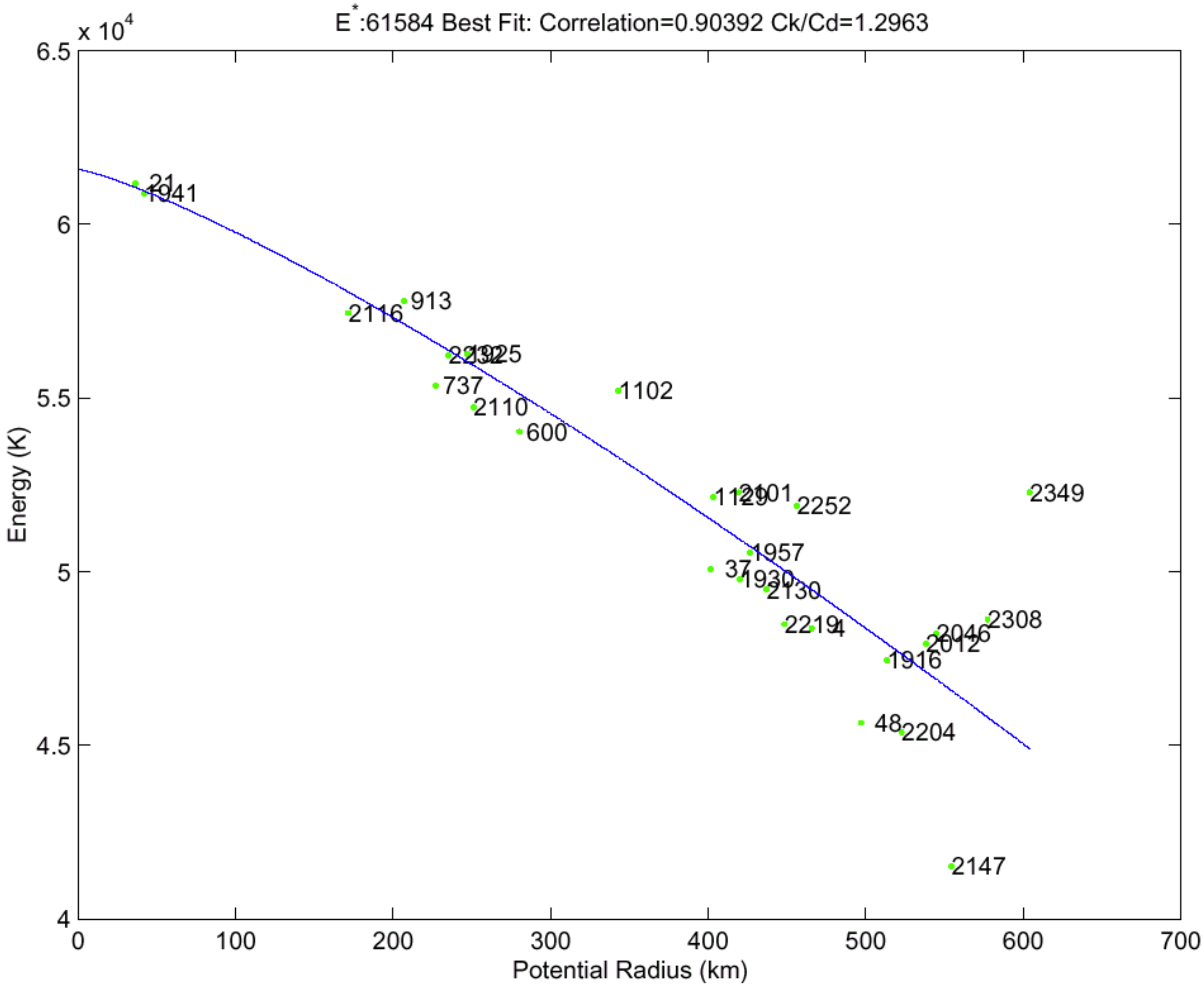

Figure 1: Moist static energy (divided by heat capacity) as a function of potential radius, which is proportional to the angular momentum per unit mass, in Hurricane Floyd (1999). The shape of this curve yields a value for the ratio of the exchange coefficients of enthalpy and momentum, as detailed by Ramstrom (2001). Here the best-fit value of this ratio is about 1.3.

The most important findings of the first year research delineated what is needed in the field experimental efforts that took place this year. (Indeed, that was the primary objective of the first year's effort.) This put us in an excellent position to specify in some detail the field experimental requirements that will yield high quality estimates of exchange coefficients in hurricanes. We put these techniques into effect in the design and execution of the CBLAST field phase this year, and believe that we now have the data in hand in which to make accurate estimates of sea-air fluxes, the ultimate objective of this work.

IMPACT/APPLICATIONS

While it is too soon to predict how the results obtained thus far will influence science, it is safe to say that any better estimates of the behavior of air-sea exchange at hurricane wind speeds will further efforts to improve hurricane intensity prediction.

TRANSITIONS

Meaningful transitions must await analysis of the field experimental data.

RELATED PROJECTS

One of the P.I.'s (Emanuel) conducted a series of experiments with an annular wind-wave flume. Equivalent 10 m winds speeds of 70 m s^{-1} can be achieved in this flume. By measuring the rate of spin down of the water mass after the airflow has been shut down, one can deduce rather precisely the drag coefficient. Similarly, the enthalpy flux coefficient is estimated by measuring the rate at which the water must be heated to keep it at room temperature. These experiments have shown that the drag coefficient increases linearly with wind speed up to about 30 m s^{-1}, but then levels off with no further increase. Experiments to deduce the enthalpy flux show a similar leveling off of the exchange coefficient at high wind speed.

Working with Ed Andreas, Emanuel has explored the effect of parameterized fluxes of momentum and enthalpy owing to sea spray on numerical simulations of tropical cyclones. This work has been published (Andreas and Emanuel, 2001).

Based on the findings of the first year's research and on the aforementioned flume experiments, the first PI submitted a theoretical paper presenting a similarity theory for air-sea fluxes at very high wind speeds (Emanuel, 2003).

SUMMARY

We have used aircraft measurements of wind, temperature and humidity in several hurricanes to deduce the drag that hurricane winds exert on the ocean surface, and the evaporation of seawater into a hurricane, which is the process that fuels the storm. Understanding the drag and the evaporation is crucial for understanding and predicting changes in hurricane wind speeds. While the estimates we made during year of the project are useful and consistent with independent estimates, their primary value was in designing a campaign for making much better measurements in hurricanes, which we put into effect during the 2003 hurricane season. We collected valuable measurements in two Atlantic hurricanes, and analysis of this data should yield accurate estimates of surface fluxes in hurricanes.

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